Original Article
Food Science and Technology
ISSN 0101-2061 (Print)
ISSN 1678-457X (Online)
DOI: https://doi.org/10.5327/fst.540

Rheological properties of *araçá-boi* poles submitted to range irradiation

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Abstract

The aim of this work was to evaluate the biotite compounds and verify the rheological behavior of manioc pulp treated with different doses of gamma radiation. The rheological parameters obtained were shear stress, strain rate, and apparent viscosity, in triplicate, for the arapa (2, 3, 4 kGy) and non-irradiated samples (control), using a Digital Viscometer II + PRO, Regular Viscometer Torque digital Brookfield viscometer, at rotational speeds of 5, 10, 20, 40, 60, 80, 100, 120, 140, 150, 160, 180, and 200 rpm, and temperatures of 5, 15, 25, 35, 45, 55, and 65°C, measured with the aid of a thermostat, at ambient atmospheric pressure. It was verified that there was no significant loss in flavonoid values; however, a decrease occurred with the application of the treatments, when compared to the control treatment. This fact may be due to the breakdown of the instability of some active compounds when exposed to ultraviolet and visible light or other sources of ionizing radiation. It was verified that after the application of the doses, the microstructure presented differentiated ramifications when compared with the control treatment. The processing of food leads to the destruction and reconstitution of the microstructure, which can be viewed as a series of restructuring and reorganization operations. Although there was a slight reduction in the flavonoid content with the doses tested, the use of the irradiation treatment is still feasible for this product. The physicochemical properties and bioactive compound characteristics of the *araçá-boi* pulp were maintained. Additionally, the irradiation process did not affect the rheological behavior of the ox spider pulps.

Keywords: non-thermal processing; bioactive compounds; vitamin c; shelf life.

Practical Application: Varying maltodextrin concentrations influence water activity, texture, and freezing rates. This helps tailor formulations based on desired shelf life, texture, or nutrient retention.

1 INTRODUCTION

A native fruit of the Amazon region, *araçá-boi* remains relatively unknown, despite its considerable economic potential. It is easy to cultivate and grows well in various types of firm soil, bearing fruit after approximately 2 years. Its abundant pulp makes it well-suited for industrial applications, such as juices, ice creams, sweets, and creams (Gomes et al., 2010).

However, its high perishability hinders its fresh consumption in many regions (Viana et al., 2012). As a result, the use of preservation technologies becomes essential to maintaining its functional and nutritional properties, enabling access to new markets and allowing consumption in its natural state without the need for processing.

Ionizing radiation is a proven safe technique with efficacy evaluated in numerous applications. Depending on the dose applied to the food, improvements in microbiological quality are observed, leading to reduced storage losses and extended shelf life. Compared to other post-production commercial treatments such as microfiltration and thermal processing, which may result in low productivity, nutrient degradation, and undesirable

Received: Jul. 31, 2025.
Accepted: Aug. 12, 2025.
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Conflict of interest: nothing to declare.
Funding: Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES).

sensory and microbiological changes due to cross-contamination gamma radiation offers distinct advantages. Following application, it is vital to assess the bioactive, microstructural, and rheological properties to ensure chemical safety and optimize processing conditions, including equipment design, piping systems, pumps, heat exchangers, evaporators, sterilizers, and mixers (Ahmed et al., 2005; Khan & Abrahem, 2010).

Although flavor and presentation play a major role in fruit pulp quality, limitations in traditional conservation methods and the challenges in defining the safest and most health-conscious combination of treatments persist. There is currently no literature on the effect of cobalt-60 gamma radiation on the rheological behavior and bioactive compounds of *araçá-boi* pulp.

Thus, the aim of this study was to evaluate the microstructure and investigate the rheological behavior of *araçá-boi* pulp subjected to different doses of gamma radiation.

1.1 Relevance of the work

The evaluation of gamma radiation effects on *araçá-boi* pulp is relevant for advancements in food preservation and safety. Maintaining rheological properties and bioactive compounds after treatment demonstrates the feasibility of using irradiation as an effective technique. Besides preserving physicochemical characteristics, this process helps extend shelf life, reduce waste, and add commercial value. The research deepens our understanding of the structural and chemical changes induced by emerging technologies, thereby strengthening both scientific and industrial applications for native tropical fruits and their derivatives.

2 MATERIAL AND METHODS

Ripe *araçá-boi* fruits, used as raw material, were sourced from Fazenda Amizade, Vila Brasil–Una/BA. The fruits were washed in running water and sanitized in chlorinated water (100 ppm) for 15 minutes. Pulp extraction was carried out at the Food Drying and Processing Laboratory of the Federal University of Campina Grande (UFCG), Campina Grande–PB. The fruits were selected, washed, and pulped using a horizontal pulping machine with a 0.8 mm diameter sieve. The resulting pulp was packed in polyethylene plastic bags containing 100 g per unit and frozen at -18°C until treatment application.

Irradiation of the *araçá-boi* pulp was conducted at the Gamma Irradiation Laboratory of the Center for Nuclear Technology Development (CDTN), located at UFPE–Recife–PE. This facility is equipped with a cobalt-60 irradiator and follows international safety standards for operation. The pulps, packaged in polyethylene bags (100 g/unit) and kept frozen at -18°C, were transported in thermal boxes, labeled with the respective doses, and carried by private vehicle from UFCG to the Metrology Laboratory at UFPE—a journey lasting approximately 4 hours. The samples were divided and subjected to different gamma irradiation doses (2, 3, and 4 kGy), with a non-irradiated sample serving as the control. After irradiation, the pulp was stored at 4°C for 60 days for characterization.

The pulp microstructure was analyzed using an optical microscope (HIROX KH1300) coupled with 2D Measure software, available at the Biomaterials Certification Laboratory (CERTBIO), Academic Unit of Materials Engineering at UFCG. The structural images were magnified to 400x and photographed for observation post-irradiation.

This experiment was carried out in the Rheology Laboratory of Agricultural Matrix Fluids, Academic Unit of Agricultural Engineering–UFCG. Rheological parameters obtained included shear stress, strain rate, and apparent viscosity, all measured in triplicate for *araçá-boi* pulp samples irradiated at different doses (2, 3, and 4 kGy) and for the control sample. Measurements were taken using a Brookfield digital viscometer DV-II+PRO, model RVT, at rotational speeds of 5, 10, 20, 40, 60, 80, 100, 120, 140, 150, 160, 180, and 200 rpm, and at temperatures of 10°C, 30°C, and 60°C, regulated by a thermostat under ambient atmospheric pressure. To convert torque readings into rheological data, the methodology proposed by Mitschka (1982) was employed.

Shear stress data as a function of strain rate were used to construct rheograms and fit rheological models: Ostwald-de-Waelle (power law), Herschel–Bulkley, and Mizrahi and Berk, using Statistica software version 5.0. The goodness-of-fit was evaluated using the coefficient of determination (R^2), representing the percentage of total variation explained. The most suitable rheological model for predicting pulp behavior was the one with R^2 values close to 1 and low chi-square (X^2) values.

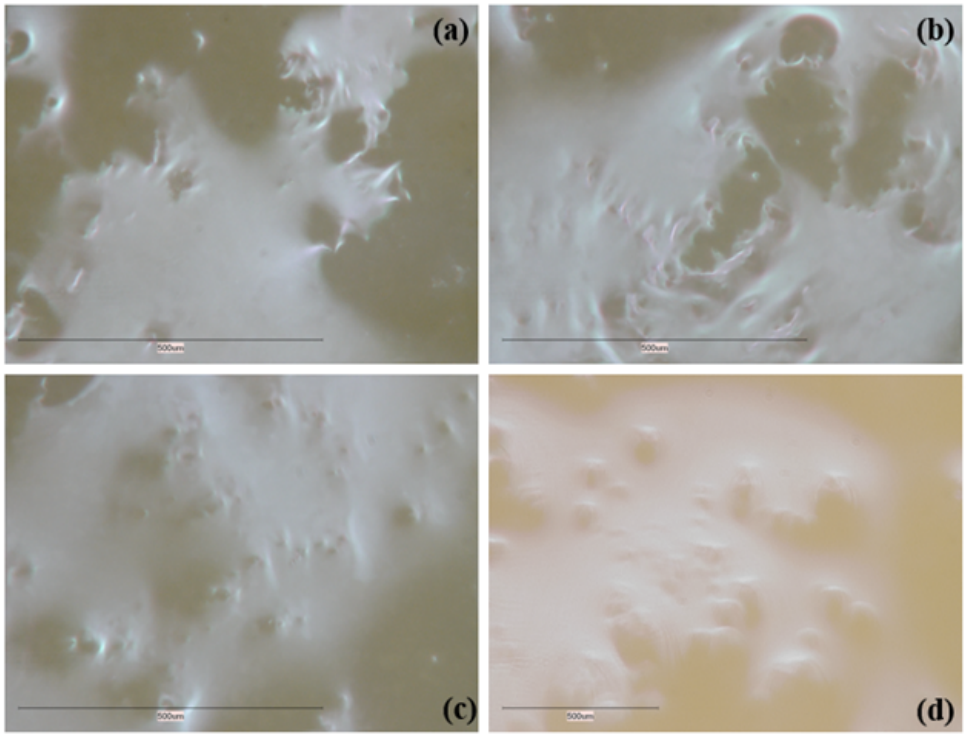
Data were subjected to analysis of variance (ANOVA), and based on the significance of the F-test, polynomial regression analysis was performed to evaluate the effect of gamma irradiation doses—testing up to the quadratic level. Significance was considered at the 5% probability level and R^2 values above 90%. SAS software version 9.3 (2011) was used for statistical analysis.

3 RESULTS

The microstructures of *araçá-boi* pulp after irradiation can be observed in Figure 1, magnified 400 times. It was noted that, following dose application, the pulp's microstructure exhibited distinct branching compared to the control treatment. When food undergoes processing, its original structure is destroyed and then reconstituted, which can be understood as a sequence of restructuring and reorganization operations.

Table 1 presents the parameters of the rheological models Ostwald-de-Waelle (power law), Mizrahi–Berk, and Herschel–Bulkley for *araçá-boi* pulp irradiated at doses of 2, 4, and 6 kGy at a temperature of 10°C, as well as the coefficients of determination (R^2) and average percentage deviations (P). It was observed that all models had R^2 values above 0.97. Among them, the Herschel–Bulkley model provided the best fit, with R^2 values exceeding 0.99 across all tested radiation doses.

Table 2 shows the parameters for the Herschel–Bulkley, Ostwald-de-Waelle (power law), and Mizrahi–Berk models at a temperature of 30°C for *araçá-boi* pulp irradiated at 2, 4, and 6 kGy, along with determination coefficients (R^2) and average percentage deviations (P). All R^2 values were above 0.921. Again, the Herschel–Bulkley model had the highest coefficients of determination, ranging from 0.985 to 0.996 for all radiation doses. However, the Mizrahi–Berk model also yielded similar performance, with R^2 values between 0.985 and 0.995.



Source: The author.

Figure 1. Photomicrographs of the guava pulp: **(a)** control treatment, **(b)** dose 2 kGy, **(c)** dose 4 kGy, and **(d)** dose 6 kGy with a magnification of 400x.

Table 1. Parameters, coefficients of determination (R^2), chi-square values (X^2), and average percentage deviations (P%) of the rheological models fitted to the rheograms of different gamma irradiation doses (2, 3, 4 kGy) and non-irradiated sample (control) at a temperature of 10°C.

	Irradiation/treatment	**K**	***n***		**R^2**	**DR**
Ostwald-de-Waelle (Power law)	0	1.000002	0.000000		1	T
	2	5.875428	0.389041		0.9731	T
	4	6.096116	0.387656		0.9783	A
	6	23.04653	0.336037		0.9784	T
	Irradiation/treatment	**K_{OM}**	**K_M**	**n_M**	**R^2**	**DR**
Mizrahi–Berk	0	−0.000003	1.000002	0.999999	1	T
	2	−64.6598	66.37428	0.026247	0.9878	A
	4	13.09624	−11.5309	−0.197962	0.9922	A
	6	5.125986	0.386135	0.296737	0.9927	A
	Irradiation/treatment	**t_{OH}**	**K_H**	**n_H**	**R^2**	**DR**
Herschel–Bulkley	0	−0.000045	1.000009	0.999998	1.000000	T
	2	−141.588	141.7071	0.044083	0.9909	A
	4	−75.0519	76.01859	0.076899	0.9919	A
	6	26.94202	3.347766	0.778677	0.9943	A

K: consistency (power law); n: flow bahavior index (power law); R^2: coefficient of determination; DR: rheological behavior type; Kom: Mizrahi-Berk parameter; Km: Mizrahi-Berk parameter; nM: flow behavior index (Mizrahi-Berk); toh: yield stress (Herschel-Bulkley); Kh: consistency (Herschel-Bulkley); nH: flow behavior index (Herschel-Bulkley).

Table 3 presents the same rheological model parameters for pulp samples irradiated at 2, 4, and 6 kGy, now at 60°C, along with the coefficients of determination (R^2) and average percentage deviations (P). For all models, R^2 values exceeded 0.96. The Herschel–Bulkley model consistently delivered the best fit, with R^2 values greater than 0.98 across all doses.

Table 2. Parameters, coefficients of determination (R^2), Chi-square (X^2) values, and mean percentage deviations (P%) of the rheological models fitted to the rheograms of different doses of gamma irradiation (2, 3, 4 kGy) and non-irradiated sample (control) at a temperature of 30°C.

	Irradiation/treatment	K	*n*		R^2	DR
Ostwald-de-Waelle (Power law)	0	10.83329	0.197991		0.9855	A
	2	3.973144	0.417212		0.9832	T
	4	3.498075	0.415492		0.9869	T
	6	11.38263	0.355120		0.921	T
	Irradiation/treatment	K_{OM}	K_M	n_M	R^2	DR
Mizrahi–Berk	0	−35.8686	39.01712	0.021846	0.9862	T
	2	−0.900022	2.757687	0.344888	0.9855	T
	4	−1.02009	2.757185	0.328344	0.989	T
	6	4.694170	0.017914	2.417895	0.99589	A
	Irradiation/treatment	t_{OH}	K_H	n_H	R^2	DR
Herschel–Bulkley	0	−116.833	126.1269	0.027128	0.9923	A
	2	−5.19673	7.891428	0.299847	0.9852	T
	4	−4.37002	6.795570	0.301771	0.9887	T
	6	22.20636	0.101716	0.388090	0.9963	A

K: consistency (power law); n: flow bahavior index (power law); R^2: coefficient of determination; DR: rheological behavior type; Kom: Mizrahi-Berk parameter; Km: Mizrahi-Berk parameter; nM: flow behavior index (Mizrahi-Berk); toh: yield stress (Herschel-Bulkley); Kh: consistency (Herschel-Bulkley); nH: flow behavior index (Herschel-Bulkley).

Table 3. Parameters, coefficients of determination (R2), Chi-square (X2) values, and mean percentage deviations (P%) of the rheological models fitted to the rheograms of different doses of gamma irradiation (2, 3, 4 kGy) and non-irradiated sample (control) at a temperature of 60°C.

	Irradiation/treatment	K	*n*		R^2	DR
Ostwald-de-Waelle (Power law)	0	5.620581	0.274416		0.969	T
	2	2.182067	0.517808		0.9949	A
	4	1.353192	0.614531		0.9851	T
	6	1.366070	0.588437		0.9631	T
	Irradiation/treatment	K_{OM}	K_M	n_M	R^2	DR
Mizrahi–Berk	0	−89.9291	91.97705	0.011131	0.9809	T
	2	1.293980	0.499184	0.876367	0.9959	A
	4	1.805463	0.099883	0.542236	0.9982	A
	6	2.056837	0.027289	0.080063	0.9975	A
	Irradiation/treatment	t_{OH}	K_H	n_H	R^2	DR
Herschel–Bulkley	0	−115.441	118.9092	0.026289	0.9891	A
	2	1.785629	1.257452	0.629310	0.9963	T
	4	3.441088	0.216238	0.013784	0.9987	A
	6	4.337771	0.058437	0.290244	0.9981	A

K: consistency (power law); n: flow bahavior index (power law); R^2: coefficient of determination; DR: rheological behavior type; Kom: Mizrahi-Berk parameter; Km: Mizrahi-Berk parameter; nM: flow behavior index (Mizrahi-Berk); toh: yield stress (Herschel-Bulkley); Kh: consistency (Herschel-Bulkley); nH: flow behavior index (Herschel-Bulkley).

The flow behavior index (n) increased with irradiation dosage; at the 2 kGy dose, the n values were lower in the Herschel–Bulkley and Mizrahi–Berk models. The flow behavior index ($n < 1$) characterizes non-Newtonian fluids of the pseudoplastic type, meaning their flow properties are independent of time.

Regarding the consistency index (K), which indicates the fluid's resistance to flow, it was noted that K values decreased as temperature increased. This behavior may be attributed to the degradation of carbohydrates in the *araçá-boi* pulp due to the combined effects of radiation and temperature, resulting in a reduction of the pulp's apparent viscosity.

In general, lower shear stress values were observed at higher temperatures under a fixed deformation rate, indicating that the apparent viscosity decreases with increasing temperature (Figure 2).

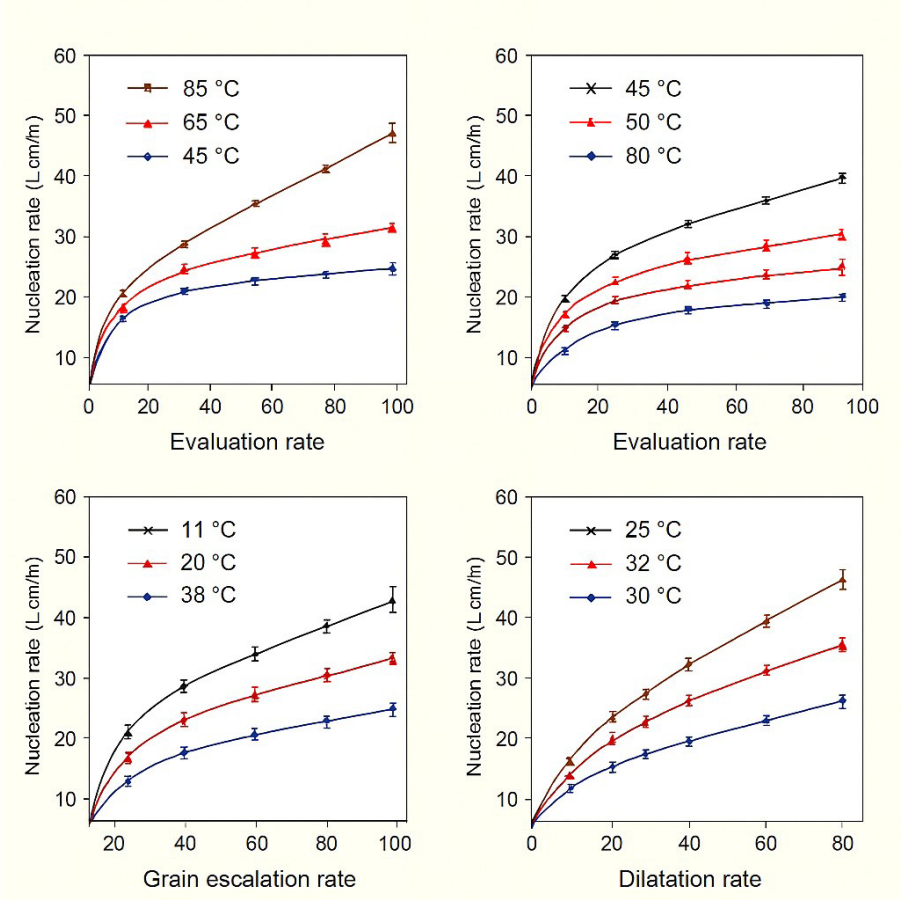


Figure 2. Rheograms of araçá-boi pulps irradiated at different gamma irradiation doses and temperatures with the Herschel–Bulkley model adjusted to the experimental data: **(a)** dose 0 KGy; **(b)** dose 2 KGy; **(c)** dose 4 KGy, and **(d)** dose 6 KGy.

4 DISCUSSION

Brito et al. (2015), when evaluating the microstructures of ice crystals formed from the available water in frozen lemon pulp at −20 ± 2°C, observed structures magnified 100 and 200 times. After the freezing process, the ice crystals exhibited tree-like branching structures, known as dendritic formations, commonly observed during solidification processes. Structural organization plays a key role in sensory properties such as color, flavor, and texture, with texture being the most affected attribute (Aguilera & Stanley, 1999). Aguilera (2005) provided a qualitative example by linking penetration force to the microstructure of cooked vegetables.

Silva et al. (2014), in their study on the rheological behavior of *umbu* pulp and jelly, obtained similar adjustments to those in this study, with the Herschel–Bulkley model providing the best fit and coefficients of determination (R^2) exceeding 0.99.

It was noted that the values for the flow behavior index (n) increased according to the irradiation dosage. According to Youssef et al. (2011), values below 1 indicated non-Newtonian fluids with time-independent pseudoplastic behavior. These authors used irradiation doses ranging from 1.0 to 2.0 kGy in refrigerated mango pulp, and obtained *n* values close to those found in this study for the 2 and 4 kGy doses.

Pseudoplasticity is a characteristic behavior of most fruit pulps. It was also observed by Oliveira et al. (2011) in *gabiroba* and guava pulps at temperatures of 20 and 35°C; by Quek et al. (2013) in *graviola* pulp at different concentrations (10–5° Brix) and temperatures ranging from 10 to 6°C.

Sousa et al. (2014) evaluated the effect of temperature on the rheological behavior of *pequi* pulp (*Caryocar coriaceum*) with different solid concentrations. This behavior is similar to the findings of Oliveira et al. (2012) for strawberry pulp, where apparent viscosity varied with shear stress across different tested temperatures. It was observed that apparent viscosity was higher at lower temperatures.

The *araçá-boi* pulps, being pseudoplastic fluids, do not exhibit a linear relationship between shear stress and strain rate.

5 CONCLUSIONS

Among the models tested, the Herschel–Bulkley model showed the best fit, with the highest coefficients of determination (R^2). The irradiation process did not affect the rheological behavior of *araçá-boi* pulp, which presented flow behavior index values lower than 1 ($n < 1$), thus characterizing them as non-Newtonian fluids with pseudoplastic behavior.

ACKNOWLEDGMENTS

The authors would like to thank the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) for the financial support.

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